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Title:

**FEEDBACK CONTROL LOOP OPERATING
SYSTEM FOR TUNABLE SOURCE**

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FEEDBACK CONTROL LOOP OPERATING
SYSTEM FOR TUNABLE SOURCE

5   ## BACKGROUND OF THE INVENTION

FIELD OF THE INVENTION

10   The present invention relates generally to systems for operating, stabilizing and/or controlling tunable light sources, for use for example in communications systems. The present invention also relates to a digital software-based system with multiple control loops for controlling a laser device, such as a distributed Bragg reflector (DBR) device.

15   ### DESCRIPTION OF THE RELATED ART

Analog-based systems, with ultra-fast control loops operating inside of other loops, have been suggested for use in controlling DBR laser devices. Such analog-based systems lack the flexibility of digital control systems, however.
20   Moreover, the analog-based systems do not provide the ability to fully automate the control process via operating software.

Multi-parameter control (wavelength, mode-hop avoidance, power and optical amplifier gain) of DBR lasers presents two fundamental problems. The
25   first is that, to mode-stabilize a DBR device, the output from the backface must be monitored during ramping of the current to the tuning section. The ramping of the tuning current tends to alter the output wavelength, which is undesirable. The other problem is that ramping of the tuning current affects the amplitude detected by the backface monitor. The characteristics of these changes are
30   fundamental to proper mode stabilization. Any changes, either deliberate or due

to aging effects, in the current to the gain section of the device will also produce changes at the backface that could be interpreted as actual changes in the tuning section. There is a need in the art for a digital feedback control system, with nesting and interaction between the various control functions, that can provide a

5   complete DBR operating control solution.

SUMMARY OF THE INVENTION

The present invention relates to a method of operating a distributed

10   Bragg reflector (DBR) laser device. The method includes the steps of using a first feedback loop to periodically adjust the temperature (or another wavelength-related characteristic) of the laser device in response to a sensed wavelength, and using a second feedback loop to periodically adjust the tuning current in response to sensed amplitude. If desired, the two feedback loops may be

15   operated at the same time.

The present invention also relates to a method of starting-up a tunable light source (such as a DBR light source). According to this aspect of the invention, a tuning current value is calculated based on stored data representative

20   of mode-hopping values for the light source. The stored data may be maintained in a look-up table, for example. In a preferred embodiment, the wavelength channel may be changed by applying a tuning current that is based on the same stored mode-hopping data.

25   The present invention also relates to a system for stabilizing the output of a laser device. The system operates by adjusting a tuning current in response to output power, and simultaneously adjusting a wavelength characteristic of the device (e.g., temperature) in response to an optically filtered fraction of the output power.

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An advantageous feature of the present invention is that numerous operational parameters for a DBR laser device can be simultaneously controlled and stabilized. In a preferred embodiment, an intelligent interaction of the feedback control loops is used to achieve the desired stabilization of multiple

5   parameters in a software-driven closed-loop feedback system.

According to yet another aspect of the invention, an etalon temperature loop is nested within a tuning current loop and a power control loop. The tuning current loop may be used to control the side mode suppression ratio

10   (SMSR) or some other operational parameter. The power control loop may be operated based on the amplitude detected by a backface monitor. This arrangement may be suitable for operating and/or stabilizing a two-section DBR laser device (i.e., one that has tuning and gain sections only).

According to another aspect of the invention, the power control loop may

15   be operated based on the output power of a semiconductor optical amplifier (SOA). In this case, the tuning current loop may be nested within the power control loop, and the temperature loop may be nested within the tuning current loop. This arrangement may be suitable for operating and/or stabilizing a four-

20   section DBR laser device (tuning, gain, optical amplifier and modulator sections).

An object of the invention is to provide a digital control system that can be flexibly adjusted for changes in operating parameters and the like via software

25   control.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing and other advantages and features of the invention will become more apparent from the detailed description of preferred embodiments given below with reference to the accompanying drawings, in which:

FIG. 1 is a schematic view of a feedback control loop operating system constructed in accordance with one aspect of the present invention.

FIG. 2 illustrates the software-based nesting and interaction of the control loops for the system of FIG. 1.

FIG. 3 is a schematic view of a system constructed in accordance with another aspect of the present invention.

FIG. 4 illustrates the nesting and interaction of the control loops for the system of FIG. 3.

FIG. 5 is a schematic view of yet another operating system constructed in accordance with the present invention.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

Referring now to the drawings, where like reference numerals designate like elements, there is shown in FIG. 1 a system 10 for operating a tunable, distributed Bragg reflector (DBR) laser device 12. The laser device 12 may be arranged to generate a light output at any one of a plurality of center wavelengths (for example, the channel wavelengths of a dense wavelength division multiplexing (DWDM) communications system), under the control of a microprocessor 14. The light output of the laser device 12 is launched into a

suitable optical communications fiber 16, and from there into a suitable communications node or other device 18, for use in the communications system as desired.

5   The illustrated laser device 12 has at least two monolithic, optically coupled sections arranged in tandem, namely, a DBR tuning section and a gain section. In addition, the device 12 has a temperature sensor 20 and a thermoelectric cooler (TEC) 22. The temperature sensor 20 and the TEC 22 may be thermally coupled to the DBR tuning and gain sections. The TEC 22 may be
10   used to control the temperature of the laser device 12, to thereby affect the wavelength of the output light (16) as discussed in more detail below.

The microprocessor 14 receives various input signals 24, 26, 28, 30 from a remote input device (not shown), a wavelength discriminator 32, the
15   temperature sensor 20, and a backface monitor 34, respectively. The microprocessor 14 provides an output signal 36 to control the TEC 22. In addition, the microprocessor 14 provides output signals 38, 40 to suitable current sources 42, 44, such that tuning and gain currents I_{tune}, I_{gain} are supplied to the DBR tuning and gain sections of the laser device 12, respectively.

20   In operation, the remote input device (not shown) is used to apply a start-up signal 24 to the microprocessor 14. The input signal 24 corresponds to a selected start-up wavelength or channel. In response, the microprocessor 14 determines a start-up tuning current I_{tune} with reference to a suitable look-up
25   table 50. In the illustrated embodiment, the look-up table 50 contains data representative of tuning currents at which DBR mode-hopping would occur. The microprocessor 14 proceeds to look up the tuning currents I_{upper}, I_{lower} that bound the selected start-up wavelength, and then sets the tuning current I_{tune} at a calculated value between the two bounding currents I_{upper}, I_{lower}.

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Thus, in a preferred embodiment of the invention, the tuning current I_{tune} initially applied to the DBR tuning section of the laser device 12 is defined according to the following expression (equation (1)):

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$$(1) \quad I_{tune} = ((I_{upper} - I_{lower})/3) + I_{lower},$$

where I_{upper} and I_{lower} are the two mode-hopping tuning currents stored in the look-up table 50, immediately above and below the selected start-up wavelength. The present invention should not be limited, however, to the details of the

10   preferred embodiments shown and described herein. In particular, the number "3" in equation (1) could be various other numbers or parameters. If desired, the number could be correlated to the exact ITU grid channel.

At the same time, a lower limit I_{limit} may be set for the tuning current I_{tune},

15   for use during operation of the tuning current loop 52 (FIG. 2). The tuning current loop 52 may contain software that is programmed to prevent the tuning current I_{tune} from becoming lower than a "dangerous" value during slope determination, to prevent unacceptable degradation of the side mode suppression ratio (SMSR) or a mode. Thus, the tuning current I_{tune} applied to

20   the DBR tuning section of the laser device 12 is maintained greater than or equal to the lower limit I_{limit}.

In a preferred embodiment of the invention, the lower limit I_{limit} may be set, for example, according to equation (2) as follows:

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$$(2) \quad I_{limit} = 1.05 * I_{lower},$$

such that the factor of safety is 5% of the lower mode-hopping current I_{lower} bounding the selected start-up wavelength, according to the data in the look-up

30   table 50. As noted above, however, the present invention should not be limited

to the preferred embodiments shown and described in detail herein. An advantage of the present invention is that relationships such as equations (1) and (2) may be readily changed by modifying the software code stored in the microprocessor 14 as needed to accommodate the particular mode/output characteristics of the laser device 12. The software also may be changed over time (e.g., the look-up table 50 may be updated), if desired, to accommodate for aging of the laser device 12 and/or other components.

The temperature loop 54 (FIG. 2) for the system 10 includes the discriminator 32 (FIG. 1) and the TEC 22 (controlled by the software-based operation of the microprocessor 14). In the illustrated embodiment, the temperature loop 54 is engaged and operated at the same time as the start-up tuning current I_{tune} is applied to the laser device 12. The temperature loop 54 is used to lock the output light (16) of the laser device 12 at a stable wavelength. The temperature loop 54, whose software is operationally nested within the tuning current loop 52 and a power control loop 56 as shown in FIG. 2, operates as follows:

The discriminator 32 generates a signal 26 representative of the wavelength of the output light in the fiber 16. The discriminator 32 may be connected to the optical fiber 16 by a suitable tap 58 of the type shown in U.S. Patent No. 6,064,681 (Ackerman), the entire disclosure of which is incorporated herein by reference. The microprocessor 14 sends a signal 36 to the TEC 22 to adjust the temperature of the laser device 12 to bring the sensed wavelength (at the tap 58) in line with the desired wavelength. The temperature loop 54 is updated periodically according to a clock in the microprocessor 14 such that the wavelength sensing and corresponding temperature updating occurs essentially continuously.

In a preferred embodiment of the invention, the temperature loop 54 is operated at an update rate that is ten to thirty times faster (depending on the I_t increment and mode being worked) than the update rate of the tuning current loop 52 (discussed in more detail below). In the embodiment shown in FIG. 2, the temperature loop 54 must be operated whenever the tuning current loop 52 is engaged, to thereby hold the output wavelength at the tap 58 within acceptable locking specifications.

The tuning current loop 52 is made up of the backface monitor 34 and the tuning current source 42 (operated under the control of output signal 38 from the microprocessor 14). The tuning current loop 52 operates to adjust, control and/or optimize the tuning current I_{tune} as a function of the power or amplitude at the laser device backface 60, as detected by the backface monitor 34.

During an initial portion of the start-up phase, while the temperature loop 54 is operating, the tuning current loop 52, under the control of suitable software in the microprocessor 14, performs a ramping up and down of the tuning current I_{tune}. In particular, the microprocessor 14 alternately adjusts the output signal 38 up and down to effectively "walk" up and down a curve representing the relationship between the backface amplitude (60) and the applied tuning current I_{tune}, for the operating mode. During the "walking" operation, the tuning current loop 52 generates point-by-point data representative of the sensed relationship between the backface amplitude (60) and the applied tuning current I_{tune}.

As the data is generated and accumulated during the "walking" phase, local slope values representative of backface amplitude as a function of tuning current are calculated, and the slope values dP/dI are stored in a suitable memory location 62 in the microprocessor 14. The temperature loop 54 is

operated throughout the generation of the slope data (62), such that the device output (16) is maintained at a fixed wavelength, and then a desired locking slope value is determined based on the stored data (62).

5   Once a value equal to or close to the desired locking slope value is defined by the microprocessor 14, an optimized tuning current I_{tune} is output to the DBR tuning section to hold the laser device 12 in the neighborhood of the desired locking slope value, at a point dependent on the percentage of the mode width that was used to scan and determine the slope value during the "walking" phase.
10   In a preferred embodiment of the invention, the scanning range is set at 5% of the mode width, but other scanning percentages may be programmed into the microprocessor 14 to accommodate other values that are considered safe with respect to mode-hopping, relative to predetermined locking requirements. The locking requirements may be determined based in part on a desired signal-to-
15   noise ratio (S/N) for the system 10.

          Once the above-described initialization operations are completed, the tuning current loop 52 may be disengaged, and then the power control loop 56 may be engaged to apply sufficient gain current I_{gain} to the laser device 12 to
20   bring the backface power (sensed by the monitor 34) up to a constant level without causing a mode-hop in the device 12. The power control loop 56 adjusts the gain current I_{gain} in response to the signals 30 from the backface monitor 34. The start-up phase is completed when the backface power (60) is brought up to the desired, constant level. In the illustrated system 10, if the
25   tuning current I_{tune} were not properly set prior to engaging the power control loop 56, then an increase in the current I_{gain} applied to the gain section of the device 12 could force a mode-hop despite operation of the temperature loop 54 (e.g., due to local heating). Consequently, in the system 10 shown in FIG. 1, it is advantageous to operate the tuning current loop 52 before the power control
30   loop 56 is first engaged by the microprocessor 14.

After the above-described start-up phase is completed, the system 10 may be operated in a channel lock mode. In the channel lock mode, the tuning current loop 52 only needs to be engaged from time to time. That is, the tuning current loop 52 may be used to adjust the tuning current I_{tune} only during such times as when the backface monitor 34 senses that the device 12 has shifted into a less than ideal SMSR position.

The tuning current loop 52 may be activated while the power control loop 56 adjusts the gain current I_{gain}. In the embodiment shown in FIG. 3, although the gain section of the device 104 is relied upon to hold a constant power output on line 16, it is not necessary to shut down the power control loop 56 during ramping of the tuning current loop 52. Since both loops 52, 56 respond to signals 30 from the same monitor 34, however, the time-constraints for the two loops 52, 56 may have to be set appropriately to prevent them from interacting with each other. If a very slow tuning current loop 52 is employed, it may be preferable to completely disengage the power control loop 56 during operation of the tuning current loop 52. In any event, the temperature loop 54 may be operated at all times to maintain the desired wavelength lock.

In a preferred embodiment of the invention, there is enough slope in each operational wavelength curve to allow a ½-channel definition via an etalon and temperature, and it appears that laser tuning via the temperature loop 54 does not shift the applicable tuning current curves relative to the wavelength curves. Thus, by using an appropriate control sign inversion -- ((REF - ETALON)/REF) vs. ((ETALON - REF)/REF) -- it is possible to lock the wavelength of the light output (16) on the opposite slopes of a 100 GHz etalon. This, with an appropriate calibration, would make it possible to achieve a 50 GHz channel spacing for the device 12.

According to yet another aspect of the invention, full channel changes may be accomplished via the same look-up table method described above in connection with the start-up phase. Moreover, once a channel tuning slope dP/dI has been defined during a prior channel change, it is stored in the second memory location 62. When the system 10 later returns to that channel, a stable tuning current I_{tune} may be applied immediately to the laser device 12, by referring to the memory 62, to maintain the desired SMSR and to avoid a mode-hop.

Prior to an actual channel change, a changed current I_{change} may be abruptly applied to the gain section of the device 12, via the second current source 44, to help ensure that the operational gain current I_{gain} has not redefined the tuning current I_{tune} that defines the point of mode-hop. The changed current I_{change} may be defined empirically as follows (equation (3)):

$$(3) \quad I_{change} = (I_{gain} \pm 4) * \Delta_{channel}^2,$$

where I_{change} is the current applied abruptly to the laser device 12, I_{gain} is the current applied to the gain section of the device 12 before the abrupt change, and $\Delta_{channel}$ is the difference between the number of the then-operating channel and the number of the channel to which the laser device 12 is to be changed.

The system 100 shown in FIG. 3 has a semiconductor optical amplifier (SOA) 102. In the illustrated system 100, the amplitude signal for the power control loop 106 (FIG. 4) is received via a suitable tap 108 at the output 110 of the SOA 102, rather than at the backface of the laser device 104. Since the tuning current loop 52 and the power control loop 106 have different inputs (the backface monitor 34 and the in-line tap 108, respectively), the tuning current loop 52 may be operationally nested entirely within the power control loop 106. That is, the tuning current loop 52 may be operated by the

microprocessor 14 whenever the power control loop 106 is engaged. In addition, the software for the system 100 may be provided with a backface loop 108 for compensating for device aging effects. The backface loop 108 may be operated based on amplitude signals 30 provided by the backface monitor 34.

5 The system 100 (FIG. 3) is otherwise the same as the system 10 shown in FIG. 1. In both systems 10, 100, the temperature loop 54 is operationally nested within the tuning current loop 52 (by suitable software stored in the processor 14).

10 Turning now to FIG. 5, there is shown yet another digital processing system 200 for operating a laser device 12. The illustrated device 12 may have a wide wavelength tuning range. Consequently, the system 200 is provided with suitable feedback loops to correct for the effects of laser device aging, among other things. In particular, the system 200 has a tuning current loop that is

15 arranged to maintain a desired relationship between the light output power P and the tuning current I_{tune}, as follows (equation (4)):

$$(4) \quad k = dP/dx,$$

20 where k is a slope constant, P is the power output by laser device 12, x = $\log(I_{tune})$, and I_{tune} is the corresponding tuning current applied to the DBR tuning section of the device 12.

Attempting to measure the slope constant k for equation (4) would be

25 problematic in the prior art, since it would be measured by varying (or dithering) the tuning current I_{tune}, and since varying the tuning current I_{tune} could cause an unwanted optical or wavelength shift in the laser device 12. For example, varying x (= $\log(I_{tune})$) by 10% could cause a change in the operational wavelength $\Delta\lambda/\lambda$ of about 50 ppm, which exceeds typical wavelength stability

30 requirements. Note that $d\lambda/dx$ is approximately constant for the laser device 12,

whereas $d\lambda/dI_{tune}$ varies widely. The latter value, $d\lambda/dI_{tune}$, may be approximately equal to $d\lambda/dx * (0.4343)/I_{tune}$.

The system 200 shown in FIG. 5 overcomes the problem of wavelength shifting caused by variations in the tuning current I_{tune} by employing a two-path wavelength control method, with appropriate bandwidth. Thus, the illustrated embodiment may be able to correct for the effects of variation in both optical power and wavelength caused by variations in the tuning current I_{tune}, and the present invention may be used to meet the tight wavelength stability specifications contemplated for DWDM communications systems. In particular, the present invention makes it possible to provide the tuning signal I_{tune} required for DBR laser operation without significantly degrading the wavelength control.

The illustrated system 200 obtains a reference voltage V_{ref} and a filtered voltage V_1 based on power transmitted through a reference tap 210 and a filtered tap 212, respectively. After normalization (and ignoring noise which is small), a voltage ratio $C(f)$ is calculated in the processor 14 as follows (equation (5)):

$$(5) \quad C(f) = V_1/V_{ref},$$

where $C(f)$ is the transmission fraction through the optical filter 214 in the filtered tap 212, f is the desired optical frequency, and for simplicity the two paths 210, 212 are assumed to be identical. The tuning current loop in the FIG. 5 system is based on the reference voltage V_1. That is, the tuning current I_{tune} is periodically adjusted based on changes in the optical power P sensed at the reference tap 210, under the control of the microprocessor 14. The temperature loop is based on the transmission fraction $C(f)$. In other words, the temperature of the TEC 22 is adjusted based on the normalized difference between the power P sensed at the reference tap 210 and the power sensed after the filter 214 in the filtered tap 212. Accordingly, the change in optical power that results from

dithering the tuning current (i.e., ΔI_{tune}) can be normalized out as far as wavelength control and the temperature loop is concerned.

Still, $d\lambda/dI_{tune}$ remains and is unwanted. In the illustrated embodiment, the significant effect of $d\lambda/dx$, or equivalently, $d\lambda/dI_{tune}$, is overcome by making the tuning current loop fully interactive with the temperature loop. With such loop interaction, the wavelength λ of the light output (16) is maintained constant by the temperature loop, even as the tuning current I_{tune} is varied by the tuning current loop. To accomplish the desired interaction, the bandwidth of the temperature loop may be significantly higher than that of the tuning current loop. The bandwidth difference permits the temperature loop to track and correct for wavelength changes introduced by changes in the tuning current I_{tune}.

To provide a rapid wavelength change (when requested via a signal 24 from the remote input device), a separate I_{tune} time constant may be switched in digitally during times of wavelength change requests. Such wavelength change requests may be accomplished by supplying a suitable signal on input line 24.

While the optical power variations discussed above should not affect the operation of the temperature loop, they may be "seen" by the system 200 if they are significant. Moreover, the loop interactions described above may introduce an error in the slope measurement that may have to be verified as acceptable. If desired, the optical power slope may be measured at two different temperatures where temperature is used to hold the output wavelength constant.

While preferred embodiments of the invention have been described and illustrated, it should be apparent that many modifications can be made to the preferred embodiments without departing from the spirit or scope of the present invention. Accordingly, the invention is not limited by the foregoing description or drawings, but is only limited by the scope of the appended claims.